

# Event characterization in (very) asymmetric collisions

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**Abstract.** Event-by-event reconstruction of the collision geometry using some incarnation of the Glauber-model is a widely accepted method in studying heavy ion collisions. While there is no known problem with the procedure when applied to the collision of two large ions, we will argue that in very asymmetric collisions, like  $p(d)+A$  with at least one hard scattering process occurring the event geometry deduced with the simple Glauber-model may be biased.

## 1. Introduction

Recent results from very asymmetric collisions at RHIC and LHC (so far  $p(d)+A$ ) provided several surprises, questioning the decade-old assumption that such reactions probe the *cold nuclear matter* (CNM) effects only, and as such, serve as reference, quasi-calibration of *no medium* effects, which can then be compared to the A+A collisions, where a hot, dense medium is formed. This prevailing view was, however, fundamentally shaken in 2013. At relatively low transverse momenta, where such phenomena are typically associated with genuine hydrodynamic flow due to a strongly interacting medium, long-range quadrupole azimuthal correlations have been observed at LHC in  $p+Pb$  collisions [1, 2, 3] and subsequently in  $d+Au$  collisions at RHIC [4]. At the high end of the available  $p_T$  range preliminary results [5] indicated a significant change of the nuclear modification factor from peripheral to central  $d+Au$  collisions, both for single particles ( $\pi^0$ ,  $\eta$ ) and reconstructed jets. This result was clearly in tension with earlier findings and theoretical expectations.

In general terms the nuclear modification factor for particle species  $X$  and nuclei  $A, B$  is defined as

$$R_{BA}^X = \frac{dN_{BA}^X/dp_T dy}{\langle N_{coll} \rangle dN_{pp}^X/dp_T dy}$$

in case of  $p(d)+A$  collisions  $B$  is simply just one proton or a deuteron. The crucial quantity is  $N_{coll}$ , the number of binary nucleon-nucleon collisions in the overlap region of the two species involved. At the very least,  $N_{coll}$  depends on the nuclear geometry: the impact parameter of the collision, the density fluctuations of the nucleus, the (energy dependent!) cross section of nucleon-nucleon collisions. In addition other kinematic and dynamic factors may play a role. In this paper we will raise the issue whether the methods to determine collision geometry and subsequent derivation of  $N_{coll}$ , worked out and functioning well for collisions of large nuclei, is unquestionably valid for very asymmetric ( $p/d+A$ ) systems as well, or there are some legitimate

concerns? Will the presence of a very hard scattering change the overall event characterization? Can such a change - if it exists - be verified experimentally?

## 2. Centrality in theory and in the experiment - large A+A collisions

Detailed study of the properties of the sQGP relies heavily on event-by-event classification of the collisions according to the (implied) collision geometry. Theorists need to know the impact parameter  $b$ , whose magnitude defines *collision centrality* in the purest sense, in order to calculate the nuclear overlap  $T_{AB}$  which then, combined with the nucleon-nucleon cross section lead to quantities like the number of participant nucleons ( $N_{part}$ ), the number of binary nucleon-nucleon collisions ( $N_{coll}$ ), as well as the spatial distribution of participating nucleons and quantities derived from it like eccentricity.

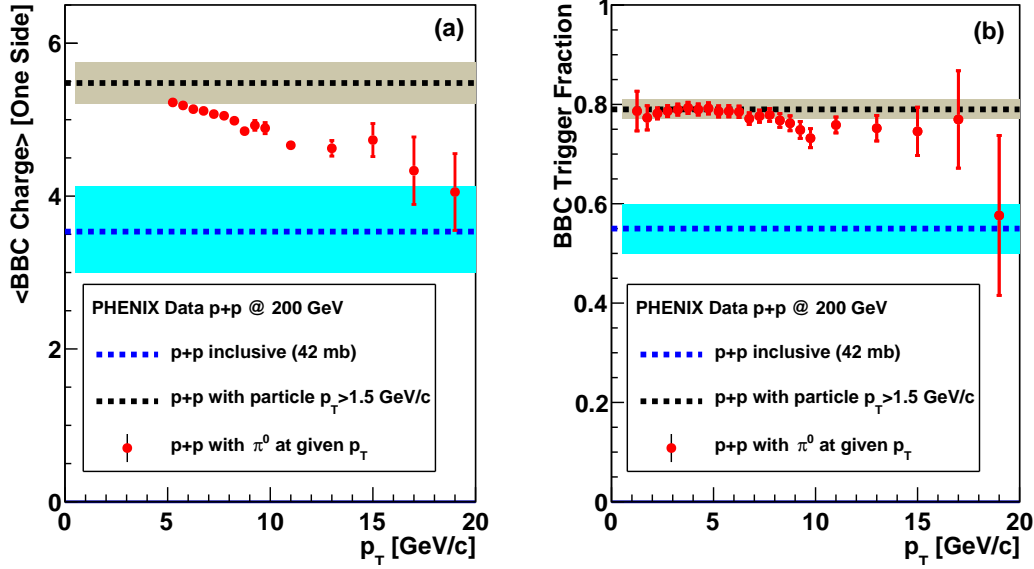
Alternately, one can sidestep the question what  $b$  is and define the collision centrality with the number of nucleons participating in the collision ( $N_{part}$ ). Just as  $b$ ,  $N_{part}$  cannot be directly determined in the experiment, it is derived from some simple *global observable* like charged particle multiplicity ( $N_{ch}$ ) or transverse energy ( $E_T$ ) in a specific pseudorapidity region. Since we are not discussing any particular experiment, we simply call the detector(s) covering this region and serving both to trigger *minimum bias* events as well as establish collision centrality, Trigger Centrality Detector(s) (TCD). It should be noted that the TCD is usually located close to beam rapidity and far from the rapidity region where the actual signal is measured. The global observables, including the signal in TCD, are correlated with the directly inaccessible  $N_{part}$  - the nature of the correlation is discussed extensively in [6] along with a historic overview how our understanding of the underlying processes evolved in the past decades. In case of large colliding nuclei and in an average event (no particles/jets above a few GeV/c observed) the  $N_{part}$  vs  $N_{ch}^{TCD}$  correlation is quite narrow, so  $N_{ch}^{TCD}$  is a reasonable proxy for the unmeasured  $N_{part}$  (of  $b$ , for that matter). The correspondence is usually established with a Glauber Monte Carlo or with some event-generator [7, 8], by convolving the  $N_{part}$  distribution with the (known or assumed) single-collision soft production, and comparing it to the measured  $N_{ch}^{TCD}$  distribution. Once a good match between model and experiment is achieved, the measured distribution is divided up to percentiles, and the corresponding  $\langle N_{part} \rangle$ ,  $\langle N_{coll} \rangle$  established from the model [7].

A crucial fact in large-on-large A+B ion collisions is that the number of participating nucleons<sup>1</sup> from *both* nuclei ( $N_{part}^A, N_{part}^B$ ) is large in all but the most extremely peripheral collisions. Combined with the observation that soft production per participant pair, the basis to determine centrality, fluctuates, collisions with  $N_{part}^A, N_{part}^B$  are practically indistinguishable from collisions with  $N_{part}^A, N_{part}^B - 1$ . In other words, even if some process would reduce (or outright eliminate) the contribution from one nucleon to  $N_{ch}$  production, this would be experimentally undetectable. We believe that this is exactly the reason why the Glauber-model works well on large-on-large systems. The same is not necessarily true when very asymmetric systems collide, like  $p(d)$  with a large nucleus A.

## 3. The case of $pp$ and $p(d) + A$ collisions

It is interesting that in the only experimentally verifiable case - namely  $pp$ -collisions - the situation is somewhat more complicated. There are two well-identified issues with  $N_{ch}^{TCD}$  production near beam rapidity: the *trigger bias* and the bias on  $N_{ch}^{TCD}$  if a high  $p_T$  particle is observed far from beam rapidity (say, at  $y = 0$ ). The two effects are demonstrated in a very compact way in Fig. 1 taken from [8]. To trigger an event requires either a coincidence of at least one hit in each of two TCD detectors (up- and downstream), called minimum bias trigger,

<sup>1</sup> We are aware that a recent paper [6] shifts the emphasis from participating nucleons to quark participants, as the scaling variable for  $N_{ch}$ , but this doesn't change the essence of our arguments.



**Figure 1.** Left (a):  $N_{ch}^{TCD}$  at  $-3.9 < \eta < -3.1$  vs the highest  $p_T$  observed in a single particle at  $|\eta| < 0.35$  in  $pp$  collisions [8]. The two dashed lines are the mean charge for events taken with minimum bias trigger (lower, blue) and requiring at least one particle with  $p_T > 1.5$  GeV/c at midrapidity. Right (b): Trigger efficiency (probability of the coincidence of at least one particle at both  $-3.9 < \eta < -3.1$  and  $3.1 < \eta < 3.9$ ) for minimum bias events (lower, blue line), events with at least one particle with  $p_T > 1.5$  at midrapidity (upper, black line), and the dependence on the highest  $p_T$  particle observed at midrapidity.

or substantial activity (at least one particle with  $p_T > 1.5$ ) at central rapidity. Note that the later trigger is significantly more efficient, i.e. once there is strong activity at mid-rapidity, *soft* production forward and backward is more likely, too. On the other hand, if the activity at midrapidity is *too* strong (rising maximum  $p_T$ ), the trigger efficiency drops a few percent, i.e. some of these high  $p_T$  events are lost and the loss has to be corrected for.

The left panel (a) is both more dramatic and more relevant for the issue at hand, namely, centrality determination in very asymmetric collisions. It shows the mean value of  $N_{ch}^{TCD}$  on one side for minimum bias triggers (blue dashed line), for  $p_T > 1.5$  at midrapidity (black dashed line) and as a function of the maximum  $p_T$  observed at midrapidity (red points). The exact reason of the relatively fast depletion of  $N_{ch}^{TCD}$  with increasing midrapidity  $p_T$  is not clear, and herein lies the potential problem in determining centrality in  $p(d)+A$  collisions from  $N_{ch}^{TCD}$ . Obviously in the asymptotic limit - two partons, both carrying  $x \approx 1$  fraction of momentum and scattering with the maximum possible  $q^2$  at mid-rapidity -  $N_{ch}^{TCD}$  goes to zero, but the probability of this happening is vanishingly small. Still it is useful to keep in mind because at *some*  $p_T$  this *kinematic* effect will start playing a role, even if we don't know (in a model-independent, experimentally verifiable way) where. It is, however, unclear whether the kinematic effect is sufficient to explain the entire drop seen in Fig. 1.

Let's turn now to  $p(d)+A$  collisions. Based on the success of the Glauber Monte Carlo in large A+A collisions it is tempting to apply the same method to derive centrality, and in fact, this is what has been done early on. In case of  $d+Au$  collisions there is an added complication from the large size of the deuteron - the two nucleons can be as far apart as 7-8 fm, the radius of the entire Au nucleus - but it also has an advantage: collisions in which only a proton or

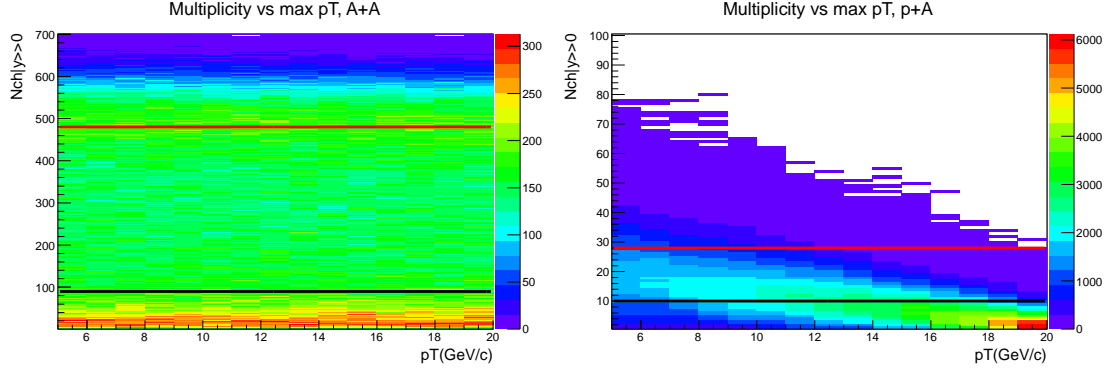
neutron interacted can be tagged, providing important cross-checks [8]. There is also a gradual shape-change and shift in rapidity of the  $N_{ch}$  distributions with centrality, measured over a wide rapidity range both at RHIC [9] and at LHC [10, 11]. This rapidity shift has been predicted (BGK triangle [12]) and it doesn't prevent us from reliably re-calibrating centrality for the *average* event. To emphasize the word *average* is more than pedantry: a comprehensive review of centrality determination [7] explicitly states that *"In heavy ion collisions, we manipulate the fact that the majority of the initial state nucleon-nucleon collisions will be analogous to minimum bias  $p+p$  collisions with a small perturbation from much rarer hard interactions."* In fact, the most authentic source, Prof. Glauber himself cautions the reader in his famous lecture, p.340 in [13]: *"...limitations... the approximate wave function (74) is only adequate for the treatment of small-angle scattering. It does not contain, in general, a correct estimate of the Fourier amplitudes corresponding to large momentum transfer."* This exactly is the justification why in the Glauber model - widely used to establish centrality - all nucleon-nucleon collisions are considered to be independent, occurring with the same cross-section and leading to similar soft particle production, irrespective of their "history"<sup>2</sup>.

What happens in *non-average* events, i.e. the ones where at least one very hard scattering occurs? As we've seen in the  $pp$  case, the TCD multiplicity - the basic building block of determining centrality - changes substantially (see Fig. 1). On the other hand in the usual procedure the measured  $N_{ch}^{TCD}$  is compared to an  $N_{part}$ -fold convolution of the detector response to an *average* nucleon-nucleon scattering. While this is *not* correct, judging from the experimentally verifiable  $pp$  case, as long as both  $N_{part}^A$  and  $N_{part}^B$  are large, the mistake in assigning a centrality class to the event is minute. However, this is *not* true in  $p(d)+A$  collisions, since there are only one or two nucleons on one side. Once a hard scattering occurred, this nucleon was necessarily part of it. In fact, in [8] the authors dealt with the problem by introducing  $p_T$ -dependent centrality bias factors, re-calculating the apparent centrality by folding  $N_{coll} - 1$ -times the *normal* nucleon-nucleon response and once the reduced one. The virtue of this approach is that it changes the generally accepted, commonly used experimental method in just one, clearly defined step. The underlying assumption, while debatable, is crisp: even if *the* projectile nucleon suffered a hard collision, in all other interactions with the target nucleons (calculated from geometry) it will behave as if nothing happened. There are some quantum mechanical (coherence) arguments to justify this assumption, although it is quite remarkable to see them in the context of defending a model whose basic tenet is the incoherent superposition of independent, identical collisions.

Other models take a different route to explain unexpected high- $p_T$   $p(d)+A$  results. In an early paper [14] the authors argue that *"Our  $pA$  collision study showed that each  $pp$  inelastic collision adds  $\sim 400$  MeV/c transverse momentum to the partons inside the proton (on average). After a few such collisions the partons gain high enough transverse momenta to become free of the proton and during this transition time they do not interact (dead time). We assume that such a proton is "lost" for the reaction and does not participate in particle production anymore. We note that such a picture corresponds to a modification of the original Glauber model."*

The color fluctuation model [15] is another attempt to explain the larger than expected  $N_{coll}$  fluctuations in  $p+A$  collisions. The model, also called Glauber-Gribov model, allows the total nucleon-nucleon cross-section  $\sigma_{tot}$  to fluctuate and thus change the distribution of wounded nucleons at a given impact parameter, or, conversely, the impact parameter distribution for a given number of wounded nucleons. On the experimental side ATLAS [10] used two Glauber-Gribov parametrizations in addition to the standard Glauber to describe their  $E_T$  measurement in  $p+Pb$  collisions.

<sup>2</sup> I.e. previous collisions and their "violence". We are aware that in a tightly coupled quantum-mechanical system the word "history" may be out of place - but that's exactly how the widely used Glauber model operates.



**Figure 2.** A simple model to illustrate possible differences between large-large and very small-large system collisions. In both panels the vertical axis is a simulated soft multiplicity ( $N_{ch}^{TCD}$ ) in the region where collision centrality is typically determined. The horizontal axes are the maximum  $p_T$  in the event; a hard collision producing high  $p_T$  proportionally decreases further soft production from this participating nucleon. Left: large A+A system (here  $A=50$ ). Right:  $p+A$  system, with  $A=197$ . Red and black lines: limits for the 20% most central and 20% most peripheral collisions, based on the multiplicity distribution at low maximum  $p_T$  (average event).

#### 4. What next?

We believe there is a potentially serious problem in establishing collision geometry in very asymmetric collisions when at least one hard scattering occurred, too. We claim the existence of the problem not because this or that particular measurement, odd or unexpected result (like  $R_{CP}$  for identified high  $p_T$  particles), but because of the experimental observation in Fig. 1 and the implausibility of the assumption that after a very hard collision the projectile nucleon keeps interacting as an unexcited, unchanged object. For arguments' sake, let's take the opposite extreme and assume that after a very hard scattering - which can turn at any point of the eikonal traversing the target nucleus - the projectile nucleon as a whole is simple “out of the pool”, stops interacting. While this is obviously unrealistic (*just as no change whatsoever is*) it's easy to build a toy model around it and check the experimental consequences.

Our toy model is a standard Glauber Monte Carlo, with randomly distributed, fixed size nucleons, the number of participants and collisions are calculated with the hard disk approximation, and the calculated soft production (charged multiplicity) is the  $N_{part}$ -fold convolution of a realistic negative binomial distribution (NBD). The only significant difference w.r.t. the standard Glauber model is that in each event we assign one of the collisions of (exactly one) projectile nucleon as hard collision, and the higher the  $p_T$  generated, the more we reduce soft production by this nucleon for the rest of its path in the target nucleus. In other words, if in the Glauber-picture the projectile nucleon scattered  $n$  times, but the  $m$ -th scattering was a hard one producing the maximum  $p_T$  in the event, then the total soft production will be calculated as an  $m$ -fold convolution of the original NBD and an  $n - m$ -fold convolution of a reduced NBD, where the mean of the reduced NBD decreases linearly with increasing maximum  $p_T$ . Since we are interested in trends, namely, whether there are noticeable changes as the maximum  $p_T$  increases, we use a flat distribution for maximum  $p_T$  (instead of a realistic spectrum each  $p_T$  is thrown with equal probability).

In Fig. 2 we show the result of our toy model for two cases: first, when two large nuclei collide (left panel,  $A=50$ ), second, when a single proton collides with a large nucleus (right,  $p+Au$ ). As already pointed out earlier, in large A+B systems, due to the large number of participants in both nuclei ( $N_{part}^A, N_{part}^B$ ) the fact that one participant from each stops contributing to soft particle production is irrelevant; the fluctuations ensure that the multiplicity distribution - consequently,

the multiplicity-based centrality classes - are unchanged irrespective of the maximum  $p_T$  observed in the event. The situation is quite different for the  $p$ +Au collision (right panel), where with increasing maximum  $p_T$  a clear depletion of soft production is observed. We believe such a *triangular* shape with  $p_T$  is a general property of very asymmetric systems, while large-on-large systems essentially don't change (they are "rectangular" with  $p_T$ ). The red and black lines indicate where the 20% most central and 20% most peripheral collisions would be if assigned based on multiplicity in the average (low  $p_T$  only) events. While there is no noticeable difference with  $p_T$  in A+A events, the character of the events in a centrality bin changes a lot in asymmetric collisions. While this toy model is deliberately simplistic, it describes features seen in actual data quite well.

In summary, we reviewed briefly how fundamental geometry like impact parameter or number of participants in heavy ion collisions are connected to experimental observables. We found that as long as large colliding systems are considered, the correspondence between the theoretical quantities and experimental observables is quite unambiguous even in the presence of a few very hard subprocesses. However, in very asymmetric, specifically  $p(d)$ +A collisions the presence of a hard process strongly biases the soft production, and, as a consequence, the derived geometric quantities as well.

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